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MECHANICAL-WAVE DISSIPATION IN THE LOWER CORONA: EMPIRICAL REQUIREMENTS FOR QUIET REGIONS

by

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I. INTRODUCTION

It is now well accepted that the heating which maintains the corona at a much higher temperature ($> 10^6$ K) than the photosphere and chromosphere is due to the dissipation of mechanical waves which are generated by the "turbulent" motions in the convection layer just below the photosphere (Kuperus, 1969). It is also fairly well established that these waves are compression waves with periods in the range 200 to 300 sec (Uchida, 1967; Kopp, 1968; Moore, 1972). However, the manner in which these waves dissipate in the corona is not well understood. In the first place, even the basic physical mechanism by which the waves are damped is not established. Possible damping mechanisms are shock-wave dissipation (Kopp, 1968), damping by thermal conduction (Sturrock, 1964; Moore, 1972), and Landau damping (D'Angelo, 1969; Moore, 1972). Each of these mechanisms seems to be capable of dissipating the compression waves in the corona. Secondly, assuming that the waves are dissipated by one of these processes, the theoretically computed rate of heating due to the dissipation at any given point in the corona is rather uncertain. For these reasons, it is of interest to empirically determine as far as possible the mechanical-wave heating in the corona.

The mechanical-wave dissipation may be characterized by the damping length L_D defined by

$$L_D \equiv - \frac{1}{F_m} \frac{dF_m}{dz} , \qquad (1)$$

where F_m is the flux of mechanical energy carried upward by the waves and z is the vertical coordinate. The purpose of this paper is to

obtain an empirical estimate of L_D in the lower corona in quiet regions. Our approach is to first empirically determine the relation between the dissipation and the temperature structure of the lower corona. We then use this relation in conjunction with the observed structure to estimate the damping length.

II. RELATION OF THE DISSIPATION AND THE TEMPERATURE STRUCTURE

It is known from XUV-resonance-line observations that between the chromosphere and the corona there is a narrow transition region in which the temperature increases from about 10^4 K to the vicinity of 10^6 K in a height range of a few thousand kilometers (Dupree and Goldberg, 1967). In the lower corona the temperature increases more slowly with height, reaching a flat maximum of about 2×10^6 K at a height of several tens of thousands of kilometers (Withbroe, 1970). The temperature level at which the transition region ends and the corona begins is somewhat arbitrary, any temperature within about a factor of two of 10^6 K being reasonable. For the purpose of this paper, it is convenient to adopt the 6×10^5 K level as the base of the corona.

We can determine the relation between the dissipation and the temperature structure of the lower corona by considering the energy balance of the corona as a whole. The heating of the corona is balanced by three modes of cooling: downward heat conduction to the transition region, radiative cooling and energy loss to the solar wind. In the following paragraphs we estimate the empirical rate of energy loss from the corona due to each of these modes.

The temperature gradient in the upper transition region and lower corona can be estimated from the observed limb brightening of XUV resonance lines emitted from these layers (Withbroe, 1970). At the 6×10^5 K level, the empirical temperature gradient obtained by Withbroe is

$$\left(\frac{dT}{dz}\right)_0 = 10^{-2.45 \pm 0.3} \text{ K cm}^{-1} . \qquad (2)$$

We use the subscript zero (0) to denote the base of the corona (where

$T \equiv T_0 \equiv 6 \times 10^5$ K). At any level in the atmosphere the heat flux F_c is proportional to the temperature gradient at that level:

$$F_c = -\kappa \frac{dT}{dz} , \qquad (3)$$

where κ is the thermal conductivity. In the temperature and pressure range of the upper transition region and lower corona, the thermal conductivity is given by

$$\kappa = 10^{-5.18} T^{2.36} \text{ erg sec}^{-1} \text{ K}^{-1} \text{ cm}^{-1} \qquad (4)$$

(Moore and Fung, 1971). Combining Equations (2), (3) and (4), we obtain

$$F_{c_0} = -10^{6.0 \pm 0.3} \text{ erg cm}^{-2} \text{ sec}^{-1} \qquad (5)$$

for the observed value of the rate of energy loss from the corona by downward heat conduction.

In quiet regions, almost all of the energy radiated from the upper transition region and the corona is contained in XUV emission lines (Pottasch, 1964). From identifications of the ions and the transitions which produce the lines in the solar XUV spectrum and from estimates of the temperatures at which these lines are most likely to be excited, Nikolsky (1969) has estimated the total radiative energy loss above the 6×10^5 K level. For the quiet solar atmosphere, Nikolsky finds from the observed spectrum that the radiative cooling rate of the corona is less than 10^5 erg cm^{-2} sec^{-1}.

Since the solar wind is highly supersonic at the orbit of the earth, the thermal energy density is negligible compared to the kinetic energy density of the streaming motion. The energy flux of the solar wind can therefore be estimated from the mass density ρ_E and velocity v_E of

the solar wind observed at the orbit of the earth. The energy flux F_{sw} at the surface of the sun necessary to maintain the solar wind is given by

$$F_{sw} = \rho_E v_E \left(\frac{1}{2} v_E^2 + \frac{GM_\odot}{R_\odot}\right) \left(\frac{R_E}{R_\odot}\right)^2 , \tag{6}$$

where $GM_\odot/R_\odot$ is (very nearly) the gravitational potential energy per unit mass at the orbit of the earth, and R_E the radius of the earth's orbit. During quiet times, the average number density of ions (mostly protons) at the earth is typically 10 cm^{-3}, and the velocity is typically 400 km sec^{-1} (Ness, 1968). These values give

$$F_{sw} = 8.7 \times 10^4 \text{ erg cm}^{-2} \text{ sec}^{-1} \tag{7}$$

for the rate of energy loss from the quiet corona to the solar wind.

The preceding estimates show that the cooling of the corona is completely dominated by downward heat conduction to the transition region. This requires that almost all of the mechanical energy flux be dissipated below the temperature maximum in the lower corona. Therefore, (1) the upward mechanical energy flux F_{m_0} which enters the corona is approximately equal to the downward heat flux F_{c_0} which flows out of the corona:

$$F_{m_0} \approx -F_{c_0} , \tag{8}$$

and (2) at each point in the corona below the temperature maximum, the rate of mechanical-wave heating per unit volume is approximately equal to the rate of conduction cooling per unit volume:

$$-\frac{dF_m}{dz} \approx \frac{dF_c}{dz} . \tag{9}$$

From Equations (1), (3), (8) and (9), we obtain

$$dF_c \approx \frac{\varkappa}{L_D}\, dT \tag{10}$$

in the corona below the temperature maximum. This is the basic relation which connects the wave dissipation with the temperature structure of the lower corona.

At the base of the corona $F_c = F_{c_0} \approx -F_{m_0}$ and $T = T_0$, and at the temperature maximum, $F_c = 0$ and $T = T_{max}$. Integration of Equation (10) from the base of the corona to the temperature maximum gives

$$-F_{c_0} \approx F_{m_0} \approx \int_{T_0}^{T_{max}} \frac{\varkappa}{L_D}\, dT \ . \tag{11}$$

$\varkappa$ is a function of temperature, and L_D may vary with height in the corona; but to illustrate the effect of the dissipation on the temperature of the corona, we temporarily assume for simplicity that both the thermal conductivity and the damping length are constant in the lower corona. Then Equation (11) becomes

$$F_{m_0} \approx \frac{\varkappa}{L_D}\,(T_{max} - T_0) \ . \tag{12}$$

Thus, we see (1) that a larger total amount of heating F_{m_0} results in a higher maximum temperature in the corona as is to be expected, but (2) that for a constant total amount of heating F_{m_0}, stronger damping (shorter damping length) results in a lower maximum temperature in the corona.

III. ESTIMATE OF THE DAMPING LENGTH

From Equation (11) we see that an "average" or representative value $\bar{L}_D$ of the damping length in the lower corona is given by

$$\bar{L}_D = \frac{1}{\left(-F_{c_0}\right)} \int_{T_0}^{T_{max}} \varkappa \, dT \; . \tag{13}$$

Using Equation (4) for $\varkappa$, we obtain

$$\bar{L}_D = 2.0 \times 10^{-6} \frac{T_{max}^{3.36}}{\left(-F_{c_0}\right)} \left[1 - \left(\frac{T_0}{T_{max}}\right)^{3.36}\right] \text{cm} \; . \tag{14}$$

Since $T_0 = 6 \times 10^5$ K and $T_{max} \approx 2 \times 10^6$ K, $(T_0/T_{max})^{3.36} \approx 1.8 \times 10^{-2}$, so that we may take

$$\bar{L}_D = 2.0 \times 10^{-6} \frac{T_{max}^{3.36}}{\left(-F_{c_0}\right)} \text{ cm} \; . \tag{15}$$

We estimate from Withbroe's (1970) results that the limb brightening data determine the value of $T_{max}^{3}/\left(-F_{c_0}\right)$ with an uncertainty of about 30%:

$$\frac{T_{max}^{3}}{\left(-F_{c_0}\right)} = 10^{12.9 \pm 0.1} \text{ K}^3 \text{ erg}^{-1} \text{ cm}^2 \text{ sec} \; . \tag{16}$$

Withbroe finds that the value of T_{max} can be determined from XUV-resonance-line intensity ratios, also with an uncertainty of about 30%:

$$T_{max} = 10^{6.3 \pm 0.1} \text{ K} \; . \tag{17}$$

Using these values in Equation (15) we obtain

$$\bar{L}_D = 3.0 \times 10^9 \text{ cm} \tag{18}$$

with an uncertainty of about 40%. This estimate of the damping length provides an observational criterion which may be used to test theoretical treatments of the mechanical-wave heating in the lower corona.

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